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Operating performance of a Joule-Brayton pumped thermal energy storage system integrated with a concentrated solar power plant

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ABSTRACT

The expected performance of an innovative Pumped Thermal Energy Storage (PTES) system based on a closed-loop Brayton-Joule cycle and integrated with a Concentrated Solar Power (CSP) plant are analysed in this study. The integrated PTES–CSP plant includes five machines (two compressors and three turbines), a central receiver tower system, three water coolers and three Thermal Energy Storage (TES) tanks, while argon and granite pebbles are chosen as working fluid and storage media, respectively. A sizing of the main components of the integrated plant has been firstly carried out for the design of an integrated PTES-CSP plant with a nominal net power of 5 MW and a nominal storage capacity of 6 equivalent hours of operation. Specific mathematical models have been developed in MATLAB-Simulink to simulate the PTES and CSP subsystem in different operating conditions, and to evaluate the thermocline profile evolution within the three storage tanks during/charging and discharging processes. A control strategy has finally been developed to determine the operating modes of the plant based on the grid service request, the solar availability, and the TES levels. The performance of the system during a summer and a winter day have been analysed considering the integration of the PTES subsystem in the Italian energy market for arbitrage. Results have demonstrated the technical feasibility of the hybridization of a PTES system with a CSP plant and the ability of the integrated system to participate to energy arbitrage, although a lower exergy roundtrip efficiency (about 54 %) has been observed with respect to the sole PTES system (about 60 %).

1. Introduction

Nowadays, the key medium-term challenge in the electricity sector is to develop technologies able to produce electric energy that would be renewable, efficient, and clean, but, at the same time, ensuring and guaranteeing dispatchability and control of the generation process [1,2]. In this way, the current energy paradigm reveals the importance of feasible, cost-effective, and large-scale energy storage systems for the adequate integration of Renewable Energy Sources (RES) into the energy market [3]. A large variety of energy storage solutions, characterized by different technology readiness level and suitable for specific applications, exists and is being investigated at present [1]. Among these energy storage technologies, the most significant ones, classified by the form of energy stored, are mechanical, electro-chemical, chemical, electrical, and thermal [4]. Some of them rely on toxic materials or have a short lifetime (as the Pb-A batteries), others are very expensive at grid-scale (for instance Li-ion batteries) or restricted by geographical or geological conditions (such as pumped hydro storage and compressed air storage) or achieve low efficiencies (like some chemical systems) [1,4]. There is a common agreement that makes Thermal Energy Storage (TES) one of the ideal candidates for long-term energy storage [5] mainly due to its low capital cost [6]. One of the most straightforward integrations of such storage systems with RES-based generators can be found in Concentrated Solar Power (CSP) plants. TES systems fulfil the requirement of increasing the current solar energy capacity factor for helping CSP technology to be highly dispatchable [7]. Furthermore, the Levelized Cost of Electricity of CSP facilities can be significantly lowered by means of the integration with TES [3,6].

A promising solution for the large-scale storage of electrical energy involving TES is the Pumped Thermal Energy Storage (PTES). In these storage systems, electricity is converted into thermal energy through a heat pump during the charging process and stored in TES reservoirs. A heat engine is then used to convert the stored heat into electrical energy during the discharging process [8,9].

PTES systems are therefore not only free of those abovementioned

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